Manufacturing of extremely narrow polymer fibers by non-diffracting beams

Jan Ježek, Tomáš Čižmár and Pavel Zemánek
Institute of Scientific Instruments, Academy of Science of the Czech Republic,
Královopolská 147, 612 64 Brno

ABSTRACT

We present an experimental way how to produce extremely narrow polymer fibers using photopolymerization. Such fibers solidify in the high intensity regions of nondiffracting zero-order Bessel beam from the solution of UV cured resin. Bessel Beams are particularly suitable for this purpose because of their narrow high intensity core and long axial region of uniform intensity. The width of the created polymer fiber is strongly dependent on the properties of the Bessel beam, used laser power and curing time. Fibers wide 2 μm were created and their length exceeded 1 cm. This length several times exceeded the axial region of the Bessel beam existence due to self-writing waveguide mechanism.

Keywords: Fiber design, Bessel beams, photopolymerization

1. INTRODUCTION

Recently the microfabrication technology using photopolymerization has been intensively studied, improved, and used in development of microstructures[1-3] and nanostructures[4], new types of micromachines[5-7], photonic crystal[8-11], etc. Special type of applications represents fabrication of polymer fibers or microstructured polymer fibers[12-16]. When a polymer fiber grew at the end of an optical fiber an interesting phenomena of self-writing has been described[17,18] and extensively studied theoretically and experimentally[19,20].
Non-diffracting beam can be an example of non-classical beam that was proposed by Durnin[21] and nowadays it plays an important role in many branches of the optics. The main reasons are that its width does not spread[22] during propagation and can even possess orbital angular momentum (optical vortex). The simplest example of these beams is so called Bessel beam (BB) because its lateral intensity profile is described by the first class Bessel function of the zero order. This beam formed behind an axicon illuminated by a Gaussiam beam (GB). BBs have been used in many unique applications[23] like microparticle guiding and delivery[24,25], microparticle and living cells sorting[26], and atom guiding[27].

2. THEORY

2.1. Bessel beam

In real circumstances it is not possible to obtain a beam that does not change its lateral properties over infinity range of propagation. In the case of the GB incident on an axicon the following scalar form of the spatial light intensity distribution in the BB can be used[28]:

$$I(r,z) = \frac{4Pk\sin\theta}{w}\frac{z}{z_{\max}}\mathrm{J}_0^2(kr\sin\theta)\exp\left\{-\frac{2z^2}{z_{\max}^2}\right\}, \qquad (1)$$

where θ is the polar angle between propagation axis of the BB and the plane waves wave-vectors forming the BB behind the axico*n (see Fig. 1):

* Further author information: jezek@isibrno.cz

15th Czech-Polish-Slovak Conference on Wave and Quantum Aspects of Contemporary Optics,
edited by Miroslav Miler, Dagmar Senderáková, Miroslav Hrabovský, Proc. of SPIE Vol. 6609, 66090J, (2007)
0277-786X/07/$18 · doi: 10.1117/12.739498

$$\theta \approx \left(\frac{\pi}{2}-\frac{\alpha}{2}\right)\left(\frac{n_a}{n_m}-1\right), \tag{2}$$

where α is the apex angle of the axicon, n_a is the refractive index of the axicon and n_m is the refractive index of the surroundings medium, k is the wavenumber of the beam in the medium, P is the power of the GB incident on the axicon, w is the half-width of the GB at the axicon, and z_{max} is the maximum propagation distance expressing the axial range where the BB exists:

$$z_{\max} = w\frac{\cos\theta}{\sin\theta}. \tag{3}$$

In the lateral plane the highest light intensity is at the centre of the BB. Let us define the radius of the BB core (RBBC) as the radial distance from the beam centre to the first intensity minimum done by:

$$r_B = \frac{2.4048}{k\sin\theta}. \tag{4}$$

Using the commercially available axicons the resulting RBBC is too wide for our purposes and therefore a telescope made from lenses L1 and L2 (see Fig. 1) is used to decrease it. The intensity of the BB passing through the telescope can be rewritten in the new coordinate system z', r' (see Fig. 1):

$$I(r',z') = \frac{4PTk\sin\theta'}{w'}\frac{z'}{z'_{\max}}\mathrm{J}_0^2(kr'\sin\theta')\exp\left\{-\frac{2z'^2}{z'^2_{\max}}\right\}, \tag{5}$$

where the parameters of the new BB are transformed as:

$$\sin\theta' = \frac{\sin\theta}{M}, \quad w' = Mw, \quad z'_{\max} = w'\frac{\cos\theta'}{\sin\theta'}, \quad r'_B = Mr_B, \tag{6}$$

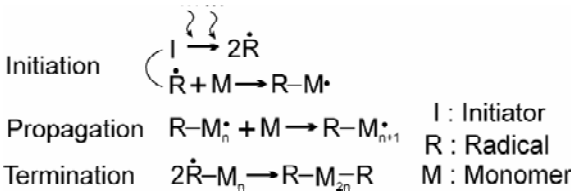
where $M=f2/f1$ is the magnification of the telescope and $f1$ or $f2$ is the focal length of the lens L1 or L2, respectively, T is the transmissivity of the telescope.

The narrow BB is formed inside a cuvette filled with a fluid of refractive index n_p. The previous results assumed the beam propagates in the air, therefore using the Snell's law for refraction into the fluid $\sin\theta'_p=\sin\theta'/n_p$ the following form of BB maximal propagation distance should be considered in the fluid:

$$z'_{\max p} = w'\frac{\cos\theta_p'}{\sin\theta_p'} \cong n_p z'_{\max}. \tag{7}$$

2.2. Photopolymerization

Compared with classical light or electron lithography, the virtue of photo-polymerization or two-photon photo-polymerization (TPP)[1] lies in its capability to make three-dimensional micro-devices[29]. This property has found applications in photonic devices and micro-machines with feature sizes close to diffraction limits[3,30]. Commercially available resin, consisting of monomers and oligomers as well as photoinitiators, is transparent to near-infrared wavelengths and allows them to penetrate deeply. When a resin absorbs a photon of proper wavelength (usually from UV region of spectra), the resultant radicals cut the double bonds of carbons in the acrylic groups in the monomers and oligomers and successively create new radicals at the ends of the monomers and oligomers. The radical combines with another monomer and the process becomes a chain reaction until the chained radical meets another chained radical[1].



The same chain reaction can be initiated if two visible photons, instead of one UV photon, are absorbed (so called two-photon absorption). Two-photon initiated laser polymerization has been shown to provide the means for two- and three-dimensional micro-fabrication with a much higher spatial resolution than conventional one-photon polymerization, because the process depends quadratically on the laser pulse energy. Therefore, only that laser beam region, where the intensity is the highest, initiates the polymerization. By scanning the laser focus according to pre-programmed patterns, designs can be faithfully replicated to matter structures.

3. EXPERIMENTAL SETUP AND RESULTS

3.1. Experimental setup

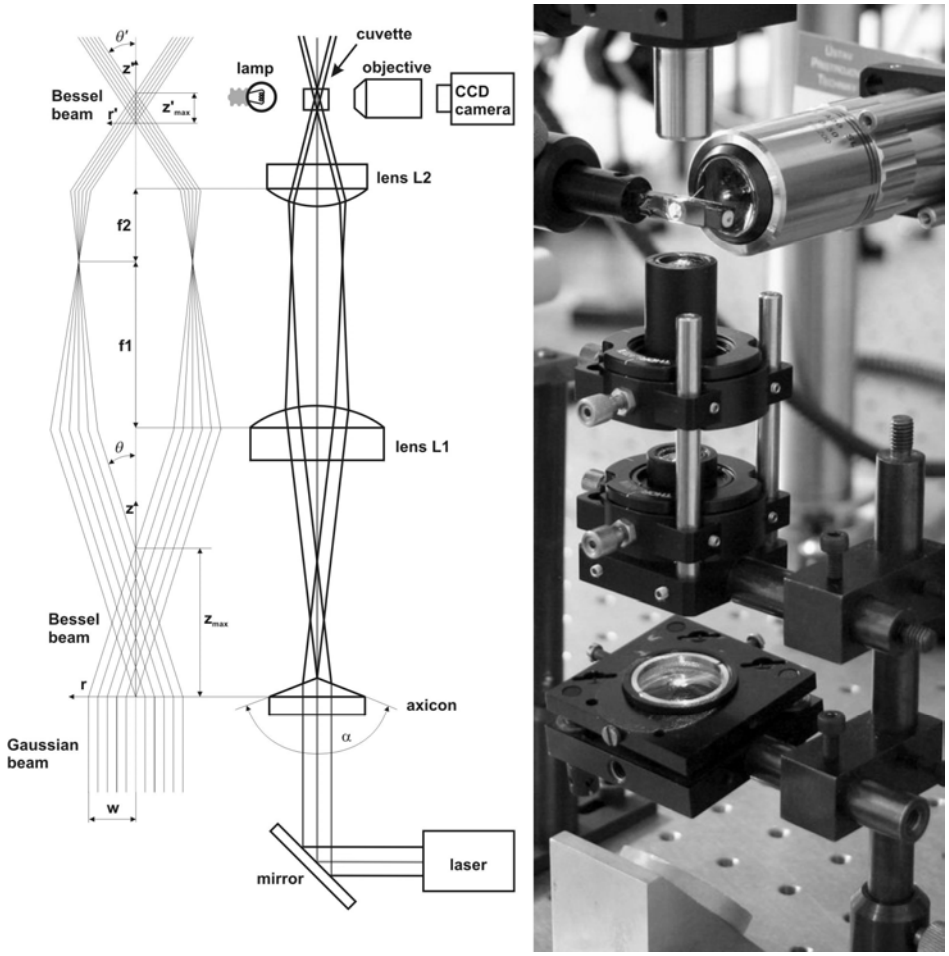


Fig. 1. Optical setup for creation polymer fiber by photopolymerization and by Bessel beam.

Figure 1 show the principle setup that was used for microfibres fabrication by means of photopolymerization and Bessel beams. The GB from continuum laser (Verdi 5W, Coherent, $\lambda = 532$ nm, maximal power 5.5 W) was transformed by axicon into Bessel beam. The core of this Bessel beam was decreased by a telescope formed by lens L1 and lens L2. Quality of the

Bessel beam was observed by an objective (Mitutoyo M Plan Apo SL 80X) and a CCD camera (CCD camera Kampro KC-381CG). Solution of monomer NOA 63 (UV light indurate optical glue Norland NOA 63, index of reflection 1.56, maximal absorption for $\lambda < 340$ nm, minimum energy for indurate 4.5 Jcm^{-2} = 0.045 $\mu J \mu m^{-2}$) is placed in cuvette. The cuvette was made from duralumin. Its cross-section was a square (side 5 mm) with two perpendicular circular open holes. These holes were covered by a microscope cover glass. The cuvette is mounted on 3D micro-positioning stage. Polymer fiber grows in the central core of the BB if the monomer is exposed by a BB. The created polymer structures were observed by the long-working-distance microscope objective (Mitutoyo M Plan Apo SL 50X) and a CCD camera (Kampro KC-381CG or IDT X-StreamVISION XS-3). We developed a technique how to extract the fibers out from the solution and carry them to a different medium or place. Optical fiber was placed on monomer solution across the central part of BB. Created fiber was stuck on optical fiber on front or lateral side and mechanically pulled out of the solution, washed by acetone and transferred. Measurement of diameter of the fiber was provided by the environmental scanning electron microscope Aquasem-Vega (ESEM, operator Ing. V. Neděla) under the high pressure conditions and without metallic coating.

3.2. Results

We study a diameter of the created fiber depending on properties of telescope's lenses (L1 and L2). We used axicon (Eksma 130-0270) with cone angle $\alpha = 170^{\circ}$ and refractive index $n_a = 1.52$ and a few different telescopes (see Fig 2.). Theoretical results are calculated by Eqs. (6 and 7). The differences between theoretical and experimental results follow from the not sufficient incident laser power to initiate polymerization in the whole area of the central core. The length of the created fiber (L_{fiber}) was determined from the side-view of the CCD camera but for wider BBs (B and C columns in Fig. 2) the length of the fiber was limited by the dimensions of the used cuvette.

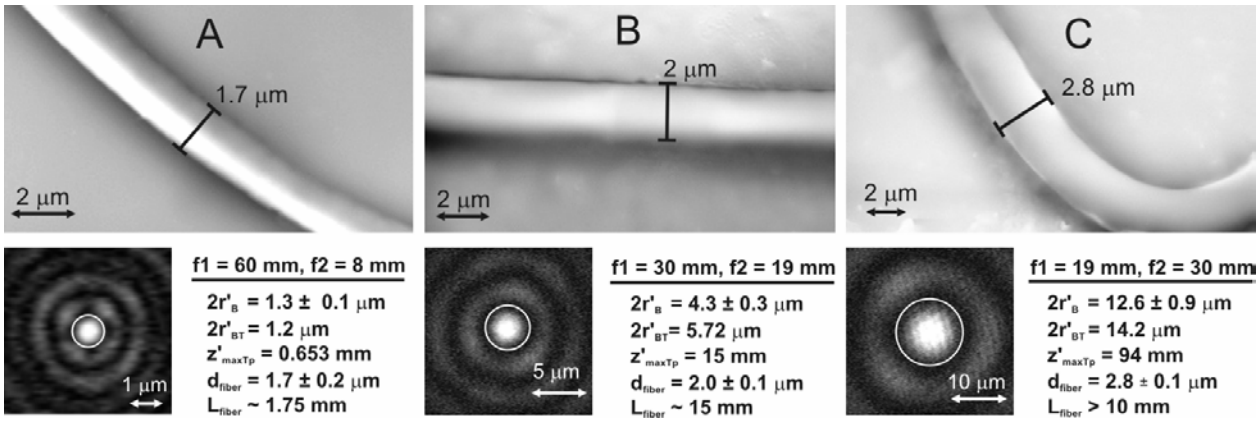


Fig. 2. *Top row:* ESEM image of the polymer fibers. In all three cases we used the same output laser power 3 W giving laser power 1.5 W in the cuvette. *Bottom row:* Lateral intensity profiles of three types of generated BBs with different diameters of the BB cores ($2\,r'_B$). Corresponding parameters of the set-up, created fiber diameter (d_{fiber}), and its length (L_{fiber}).

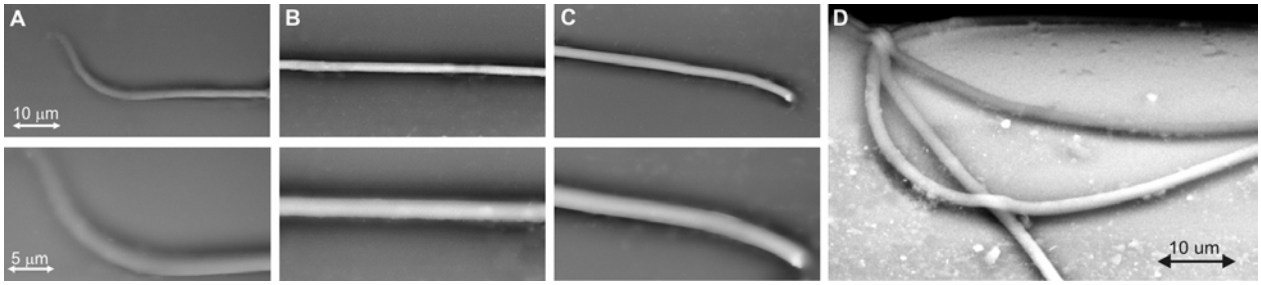


Fig. 3. ESEM images of the left (**A**), middle (**B**) and right (**C**) part of one fiber long 15 mm (see the column **B** in Fig. 2.). Each of the image rows keeps the same scale but uses different magnifications to demonstrate the fiber homogeneity. The

picture **D** demonstrates crossing of fibers lying on the surface of the optical fiber. The polymer fibers were free and could be rearranged by a micromanipulator. Contaminations on the surfaces evolved during the washing and transport of the sample to the ESEM.

We used a different setup where the BB z'_{maxTp} was short enough to observe both - the whole BB and the manufactured fiber by the CCD from a side. The setup consisted of the axicon with the apex angle $\alpha = 179.065°$ and a combination of lenses with focal lengths $f1 = 500$ mm and $f2 = 8$ mm. The generated BB had the following parameters: $2r'_B \sim 1.5$ μm and z'_{maxTp} ~100 μm. The top plot in Fig. 4 shows the calculated on-axis intensity profile in the BB using Eq. 5 and the images bellow show the side view of the created fiber if the image background at zero time was subtracted. Obviously the fiber grew asymmetrically with respect to the high intensity part of the BB. This also proves that the self-writing mechanism prolongs the fiber in the direction of the BB propagation.

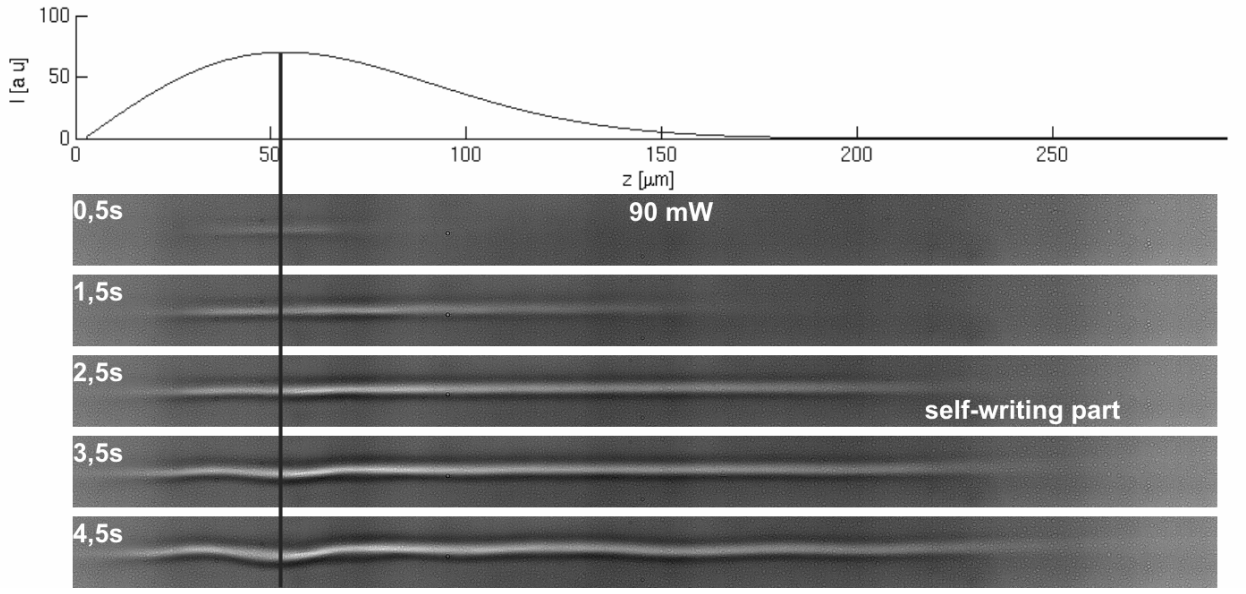


Fig. 4. Formation of the polymer fiber in the short BB. The BB core radius was 0.8 μm and the maximum propagation distance of the BB was about 100 μm. The laser power in the cuvette was 90 mW. The top plot shows the calculated on-axis intensity profile of the BB for the parameters used in the experiment.

4. CONCLUSION

In this paper we presented an experimental way how to produce extremely narrow polymer fibers using photopolymerization and Bessel beam. The width of the created polymer fiber is strongly dependent on the properties of the Bessel beam, used laser power and curing time. We demonstrate to create polymer fibers with wide 2 μm and length exceeded 1 cm. This length several times exceeded the axial region of the Bessel beam existence due to self-writing waveguide mechanism. Visualization of the fibers by environmental scanning electron microscope reveals that their surface is smooth and width is uniform along the fiber length.

5. ACKNOWLEDGEMENTS

This work was partially supported by the Institutional Research Plan of the Institute of Scientific Instruments (AV0Z20650511), Grant Agency of the Academy of Sciences (KJB2065404) and Ministry of Education, Youth, and Sports of the Czech Republic (LC06007). The authors are obliged to Ing. V. Neděla for taking the images and data from ESEM.

REFERENCES

1. S. Maruo, O. Nakamura and S. Kawata, "Three-dimensional microfabrication with two-photon-absorbed photopolymerization," *Optics Letters* 22, 132-134 (1997).
2. Z. Bayindir, Y. Sun, M. J. Naughtona, C. N. LaFratta, T. Baldacchini, J. T. Fourkas, J. Stewart, B. E. A. Saleh, M. C. Teich, "Polymer microcantilevers fabricated via multiphoton absorption polymerization," *Appl. Phys. Lett.* 86, 064105 (2005).
3. B. H. Cumpston, S. P. Ananthavel, S. Barlow, D. L. Dyer, J. E. Ehrlich, L. L. Erskine, A. A. Heikal, S. M. Kuebler, I.-Y. S. Lee, D. McCord-Maughon, J. Qin, H. Röckel, M. Rumi, X. Wu, S. R. Marder and J. W. Perry, "Two-photon polymerization initiators for three-dimensional optical data storage and microfabrication," *Nature* 398, 51-54 (1999).
4. F. Formanek, N. Takeyasu, T. Tanaka, K. Chiyoda, A. Ishikawa, and S. Kawata, "Three-dimensional fabrication of metallic nanostructures over large areas by two-photon polymerization," *Opt. Express* 14, 800-809 (2006).
5. P. Galajda and P. Ormos, "Complex micromachines produced and driven by light," *Appl. Phys. Lett.* 78, 249-251 (2001).
6. P. Galajda and P. Ormos, "Orientation of flat particles in optical tweezers by linearly polarized light," *Opt. Express* 11, 446-451 (2003).
7. S. Maruo, K. Ikuta and H. Korugi, "Submicron manipulation tools driven by light in a liquid," *Appl. Phys. Lett.* 82, 133-135 (2003).
8. M. Campbell, D. N. Sharp, M. T. Harrison, R. G. Denning, and A. J. Turberfeld, "Fabrication of photonic crystals for the visible spectrum by holographic lithography," *Nature* 404, 53-56 (2000).
9. M. J. Escuti, J. Qi , and G.P. Crawford, "Tunable face-centered-cubic photonic crystal formed in holographic polymer dispersed liquid crystals," *Opt. Lett.* 28, 522-524 (2003).
10. K. Kaneko, H. B. Sun, X. M. Duan, and S. Kawata, "Submicron diamond-lattice photonic crystals produced by two-photon laser nanofabrication," *Appl. Phys. Lett.* 83, 2091-2093 (2003).
11. R. C. Rumpf, and E. G. Johnson, "Comprehensive modeling of near-field nanopatterning," *Opt. Express* 13, 7198-7208 (2005).
12. C. Jensen-McMullin, H. P. Lee, and E. R. Lyons, "Demonstration of trapping, motion control, sensing and fluorescence detection of polystyrene beads in a multi-fiber optical trap," *Opt. Express* 13, 2634-2642 (2005).
13. M. van Eijkelenborg, "Imaging with microstructured polymer fibre," *Opt. Express* 12, 342-346 (2004)
14. J. Zagari, A. Argyros, N. A. Issa, G. Barton, G. Henry, M. C. J. Large, L. Poladian, and M. A. van Eijkelenborg, "Small-core single-mode microstructured polymer optical fiber with large external diameter," *Opt. Letters* 29, 1560-1560 (2004).
15. A. Argyros, M. A. van Eijkelenborg, M. C. J. Large, and I. M. Bassett, "Hollow-core microstructured polymer optical fiber," *Opt. Letters* 31, 172-174 (2006).
16. T. Yamashita, and M. Kagami, "Fabrication of Light-Induced Self-Written Waveguides With a W-Shaped Refractive Index Profile," *J. Light. Tech.* 23, 2542-2548 (2005).
17. S. J. Frisken, "Light-induced optical waveguide uptapers," *Opt. Letters* 19, 1035-1037 (1993).
18. A. S. Kewitsch and A. Yariv, "Self-focusing and self-trapping of optical beams upon photopolymerization," *Opt. Letters* 21, 24-26 (1996).
19. T. M. Monroi, C. M. de Sterke and L. Poladian, "Catching light in its own trap," *J. of Modern Optics* 48, 191-238 (2001).
20. K. D. Dorkenoo, F. Gillot, O. Crégut, Y. Sonnefraud, A. Fort, and H. Leblond, "Control of the Refractive Index in Photopolymerizable Materials for (2 + 1)D SolitaryWave Guide Formation," *Phys. Rev. Lett.* 93, 143905 (2004).
21. J. Durnin, J. J. Miceli, and J. H. Eberly, "Difraction-free beams," *Phys. Rev. Lett.* 58, 1499-1501 (1987).
22. Z. Bouchal, J. Wagner, M. Chlup, "Self-reconstruction of a distorted nondiffracting beam," *Opt. Com.* 251, 207-211 (1998).
23. D. McGloin, and K. Dholakia, "Bessel beam: diffraction in a new light," *Cont. Phys.* 46, 15-28 (2005).
24. T. Čižmár, V. Garcés-Chávez, K. Dholakia, and P. Zemánek, "Optical conveyor belt for delivery of submicron objects," *Appl. Phys. Lett.* 86, 174101 (2005).

25. T. Čižmár, V. Kollárová, Z. Bouchal and P. Zemánek, "Sub-micron particle organization by self-imaging of non-diffracting beams," *New Journal of Physics* 8, 43 (2006).
26. L. Paterson, E. Papagiakoumou, G. Milne, V. Garcés-Chávez, S. A. Tatarkova, W. Sibbett, F. J. Gunn-Moore, P. E. Bryant, A. C. Riches and K. Dholakia, "Light-induced cell separation in a tailored optical landscape," *Appl. Phys. Lett.* 87, 123901 (2005).
27. K. Okamoto, Y. Inouye and S. Kawata, "Use of Bessel J(1) laser beam to focus an atomic beam into a nano-scale dot," *Jpn. J. of Appl. Phys. Part 1* 40, 4544-4548 (2001).
28. V. Jarutis, R. Paškauskas and A. Stabinis, "Focusing of Laguerre-Gaussian beams by axicon", *Opt. Communications* 184, 105-112 (2000).
29. K.D. Belfield, K.J. Schafer, Y. Liu, J. Liu, X. Ren and E.W. Van Stryland, "Multiphoton-absorbing organic materials for microfabrication, emerging optical applications and non-destructive three-dimensional imaging," *J. Phys. Org. Chem.* 13, 837-849 (2000).
30. P. Borowicz, J. Hotta, K. Sasaki and H. Masuhara, "Chemical and optical mechanism of microparticle formation of poly(N-vinylcarbazole) in N,N-dimethylformamide by photon pressure of a focused near-infrared laser beam," *J. Phys. Chem. B* 102, 1896-1901 (1998).